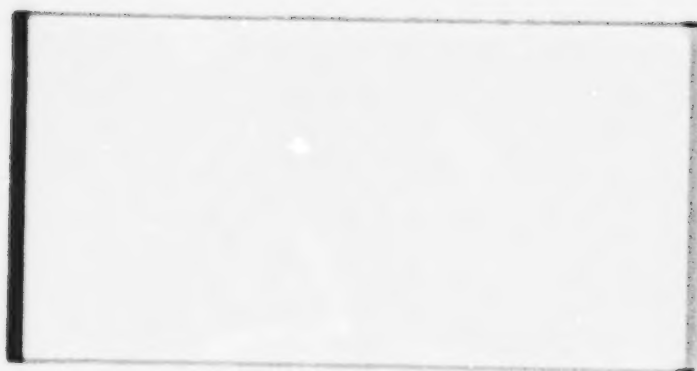


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PROGRESS IN WELDING STUDIES FOR CANADIAN NUCLEAR FUEL WASTE DISPOSAL CONTAINERS

Report No 85-98-K

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ABSTRACT

This report describes the progress in the development of closure-welding technology for Canadian nuclear fuel waste disposal containers. Titanium, copper and Inconel 625 are being investigated as candidate materials for fabrication of these containers. Gas-tungsten-arc welding, gas metal-arc-welding, resistance-heated diffusion bonding and electron beam welding have been evaluated as candidate closure welding processes. Characteristic weldment properties, relative merits of welding techniques, suitable weld joint configurations and fit-up tolerances, and welding parameter control ranges have been identified for various container designs. Furthermore, the automation requirements for candidate welding processes have been assessed. Progress in the development of a computer-controlled remote gas-shielded arc welding system is described.

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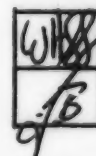
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EXECUTIVE SUMMARY

PROGRESS IN WELDING STUDIES FOR CANADIAN
NUCLEAR FUEL WASTE DISPOSAL CONTAINERS

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An extensive program is in progress in the development of closure-welding technology for nuclear fuel waste disposal containers. It has been demonstrated that gas-tungsten-arc (GTA) welding, resistance-heated diffusion (R/D) bonding and electron beam (EB) welding produce acceptable welds in titanium, although for the relatively thin-walled supported-shell container design, EB welding appears to be least attractive. Among various techniques being considered, EB welding appears to be an ideal process for welding thick copper without preheating. Thick copper can also be joined using the gas-metal-arc welding process with or without preheating, but extremely high welding currents (> 1000 A) are required when preheating is not used. R/D bonding is found to be unsuitable for joining Inconel 625 as a result of excessive interfacial oxide formation. EB welding appears to be a feasible process for the final closure of stressed-shell Inconel containers. The relative merit, welding parameter control range, weld joint design and fit-up tolerances, and requirements for automation have also been identified for various containers. The development of a computer-controlled remote arc welding capability is also in progress.



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To Mr. H.N. Issac
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PROGRESS IN WELDING STUDIES FOR CANADIAN
NUCLEAR FUEL WASTE DISPOSAL CONTAINERS

1.0 INTRODUCTION

1.1 Nuclear Fuel Waste Disposal Program

Used fuel from CANDU nuclear reactors is to be isolated from the biosphere for significant periods of time. One of the current concepts in the Canadian Nuclear Fuel Waste Management Program involves isolation of the waste form in a corrosion-resistant container and disposal in a deep, hard-rock vault/1,2/. Most of the container engineering has focused on a 500-year containment period/2,3/. The container must be capable of withstanding the hydrostatic pressure of a flooded 1000 m-deep vault (~9.8 MPa) at temperatures of 150°C for the design lifetime of the container. Furthermore, the container material must be corrosion-resistant in the disposal vault environment. Copper, commercially pure and low alloy titanium, Inconel 625 and 316 L stainless steel have been identified as candidate container materials/4/. Two basic container design concepts are being studied:

1. Stressed-shell designs in which the container is thick enough to withstand the hydrostatic pressure in a flooded disposal vault (see Figure 1)/5/.
2. Supported-shell designs in which a container with a thinner shell (thickness determined by corrosion resistance and handling stresses) is internally supported by, for example, a metal matrix, a packed particulate or a rigid internal structure (see Figures 2, 3, 4)/3,6,7,8/.

As part of its Technical Assistance Program to Atomic Energy of Canada Ltd (AECL) in the Canadian Nuclear Fuel Waste Management Program, Ontario Hydro is performing studies related to containment and immobilization. Because the used fuel is highly

radioactive, all handling, final closure welding, inspection and, if necessary, repair of a loaded container must be done remotely. The present report describes progress to date in the development of welding technology for the final closure of nuclear fuel waste disposal containers.

1.2 Container Welding Program

The Welding Unit of the Metallurgical Research Department of Ontario Hydro is carrying out an extensive research program with the assistance of AECL, Bristol Aerospace Ltd, the Welding Institute of Canada and the National Research Council of Canada in the development of closure-welding techniques for nuclear fuel waste disposal containers. The work packages are identified as follows:

1. Carry out feasibility studies to identify the optimum welding process for each of the container designs under consideration; define optimum weld joint designs, fit-up tolerances, and optimum welding procedures and welding parameter control ranges for the final closure welds.
2. Work with container designers as required and provide technical assistance for prototype container fabrication and closure welding.
3. Work in close liaison with parallel programs on detailed material properties, fracture mechanics and non-destructive evaluation technology to define acceptance standards necessary for quality assurance of the final closure weld.
4. Identify the requirements for remote-controlled welding, including seam tracking and welding parameter monitoring, and develop remote welding equipment as required.

2.0 PROGRESS IN WELDING STUDIES

2.1 Titanium

Grade 2 commercially pure titanium and Grade 12 titanium are being considered as candidate materials for supported-shell container designs (thickness in the range of 4 to 6 mm) and the stressed-shell container design (thickness > 25 mm). Gas-tungsten-arc (GTA) welding, resistance-heated diffusion (R/D) bonding and electron beam (EB) welding are being evaluated for final closure of these containers. All the welding studies to date have been carried out on Grade 2 titanium, but will be extended to Grade 12 titanium in the later stages of this project.

2.1.1 Gas-Tungsten-Arc Welding of Titanium

It is generally known that pure titanium and its alloys readily react with and become embrittled by available contaminants such as oxygen and nitrogen in the weld zone. An investigation was carried out to identify the limits of these contaminants and to define their effects on the mechanical properties of titanium fusion welds/9/.

In this study, titanium welds were made under high purity argon and pre-mixed argon-air mixtures using the manual GTA welding process. The test results showed that titanium welds can tolerate a maximum level of 0.3% air contamination in the argon shielding gas without severe loss of weld ductility and still display satisfactory mechanical properties. It has also been demonstrated that contamination-free titanium welds can be made with great reliability using proper shielding devices. It is thus suggested that open air (out-of-chamber) arc-welding techniques should be pursued for the final closure of titanium containers. There is no justification for the use of in-chamber welding, which is both time-consuming and expensive. It was shown that weld surface discoloration can be used as an indication of gas shielding effectiveness and thus to qualitatively estimate the degree of air contamination in the shielding gas and in the titanium fusion welds.

In addition, the increase in weld zone hardness, over that of the parent metal can be used to estimate qualitatively the degree of air contamination in titanium welds. A maximum allowable weld hardness increase of 30 Vickers points should be used to obtain the most satisfactory weldment properties. On the other hand, transverse tension test results showed no effects of air contamination in titanium weldments because of non-uniform straining in the gauge length of the tested coupons. Other mechanical tests, such as longitudinal all-weld-metal tension tests and bend tests, which are more sensitive to air contamination in titanium welds, must be used as supplements to the transverse tension tests for complete quantitative evaluation of titanium weldment properties.

In mechanized pulsed-current GTA welding studies, it has been demonstrated that sound single-vee groove welds can be made in Grade 2 titanium plates 3.6 to 6.4 mm thick without using a backing gas shield. Both visual appearance and hardness test results indicated no excessive air contamination. Based on these test results, a weld joint design employing a feather edge preparation and integral backing support has been used in the development of GTA welding procedures for the final closure joint of titanium containers (see Figure 5). The cross-section of a typical GTA titanium weld is shown in Figure 6. It has

been shown that a relatively large root opening (≥ 2.5 mm) and a small included angle (30 to 45°) are necessary to ensure complete root fusion and a satisfactory weld bead surface profile, particularly for those joints displaying poor fit-up. The test results also show that a maximum high/low misfit of -2 mm can be tolerated in this joint design with appropriate welding procedures, for thicknesses from 4.8 to 6.4 mm. However, fit-up tolerances decrease with decreasing metal thickness.

At the present time welding trials are being carried out on small scale titanium pipe mock-ups to develop procedural "tolerance boxes" for welding parameters such as wire feed rate, pulse current, background current, arc voltage and welding speed. These will be used for in-process monitoring control to ensure satisfactory weldment properties.

2.1.2 Resistance-Heated Diffusion Bonding of Titanium

Feasibility studies show that sound resistance-heated diffusion bonds can readily be made in Grade 2 titanium flat strips and interference-fit rings/10,11,12,13/. The recommended joint design for closure by resistance-heated diffusion bonding and a cross-section of a typical titanium resistance-heated diffusion bond are shown in Figures 7 and 8, respectively. A typical titanium resistance-heated diffusion bonded ring mock-up is shown in Figure 9. This solid-state bonding process, performed at temperatures significantly below the melting temperature of pure titanium, has several distinct advantages over fusion-welding techniques, including minimal risk of contamination or excessive grain growth, and reduced distortion. Furthermore, the process is extremely attractive for remote joining because it is simple, rugged and easily controllable.

Titanium workpieces can be bonded in open air (with no gas shielding) and still display satisfactory mechanical properties over a wide range of bonding parameters/10,11/. For a solid-state bonding process, it has been shown that there is no correlation between surface contamination and bulk metal contamination. No joint embrittlement is detected even in those bonded samples displaying severe surface oxidation or surface contamination. Work by others has shown that the corrosion resistance of pure titanium is closely related to the thickness and morphology of the surface oxide film/14,15/. Relatively thin and adherent oxide films have been shown to provide optimum corrosion resistance in pure titanium. In contrast, relatively thick and porous films are non-protective and may reduce the corrosion resistance. Previous studies in this program/10,11/ have shown that procedures can be readily established for relatively thin titanium (≤ 4 mm) to produce excellent bond quality and a smooth electrode wheel contact surface with minimal surface oxidation.

Further experimental studies/12,13/ showed that high bonding current and long heating time are required for bonding 6.4 mm thick titanium rings, causing excessive surface heating and severe surface oxidation and deformation.

Severe surface heating appears to result from a high current density at the contact surface, which is critically dependent on the bonding current and the electrode contact area. The severity of surface oxidation and deformation can be controlled by adjusting bonding conditions, but the scope for adjustment is limited by the need for high bonding current and long heating time to obtain sound bonds. Significant improvement of surface condition can likely be achieved by modification of the electrode wheel configuration, thereby lowering the current density.

In the centre-bond joint configuration shown in Figure 7, a crevice is present near the top edge of the joint. In order to avoid crevice corrosion, the development of an edge-bonding technique is in progress. A flanged electrode wheel is used for the ID surface to bond to the top edge of the joint and thereby close the crevice.

Non-destructive testing studies showed that inadequate bonding, and bond width, and defects induced by foreign objects such as grease, paint and glass beads at the joint can be readily detected by ultrasonic inspection, with no requirement for prior surface grinding/11,16/.

In summary, the experimental work to date has shown that resistance-heated diffusion bonding is both feasible and promising for the final closure of supported-shell titanium containers. Sound bonding procedures have been established for closure of the thin-walled (-4 mm thick) packed particulate container design. However, more experimental work in procedure development is required for container designs having a somewhat thicker shell, such as the prototype structurally-supported container (6.4 mm thick) to reduce surface oxidation and deformation. The development of an edge-bonding technique is in progress to close the crevice present near the top edge of the joint. Corrosion studies should also be performed to determine the degree of surface oxidation providing optimum corrosion resistance, with the test results used in the selection of optimum bonding procedures. The effect of joint fit-up on bond quality should also be investigated.

2.1.3 Electron Beam Welding of Titanium

Feasibility studies have shown that square butt, electron beam welds displaying satisfactory mechanical properties can be made in 12.7 mm (0.5 in) thick Grade 2 titanium plates/17/. The

cross-section of a typical titanium electron beam weld is shown in Figure 11. The test results show that in developing the electron beam welding technique, efforts should be made to eliminate crown undercutting and to have good grain size control in the fusion zone. A preferred joint design with an integral backing support has been suggested for the final closure of titanium containers, aimed at eliminating problems such as root drop-through and weld metal spatter on the weld back-face, often encountered in full-penetration welds. This joint design is similar to that used for the copper container, shown in Figure 11. Being a high energy density process, electron beam welding is particularly attractive for welding thick titanium. The energy required to weld a joint with a given thickness is considerably less than that required by conventional arc welding processes, which minimizes distortion and heat-affected zone size. However, closer weld joint fit-up is required for electron beam welding than for arc welding. For welding thin titanium, electron beam welding appears to have no distinct advantages over arc welding or resistance-heated diffusion bonding. Electron beam welding is, therefore, considered to be a viable process only for the final closure of thick-walled stressed-shell titanium containers. Activities in the development of electron beam welding procedures for thick titanium are at a halt at the present time, and likely would be resumed only if the titanium stressed-shell container is re-established as one of the more likely candidates among the various container designs.

2.2 Copper

Copper, in the thickness range of 19-25 mm, is an alternative material for supported-shell containers. A design has been developed for a copper-shell structurally-supported container^{8/} and work is underway to design a copper shell metal-matrix container. Electrolytic tough-pitch (ETP) copper, oxygen-free (OF) copper and phosphorus-deoxidized copper are being considered as candidate materials. Electron beam welding and gas-metal-arc welding are under investigation for the fabrication and closure of these copper containers.

2.2.1 Electron Beam Welding of Copper

Feasibility studies have shown that single pass square butt electron beam welds (depth of penetration > 25 mm) can be made in 25 mm thick ETP copper and OF copper plates, and small-scale pipe mock-ups^{18,19,20,21/}. The weld joint design used in these studies is shown in Figure 11. A typical copper electron beam welded pipe mock-up and the cross-section of a typical copper EB weld are shown in Figures 12 and 13, respectively. The test results show that OF copper exhibits better weldability than ETP

copper. EB welds in OF copper can be made over a wide range of beam power/welding speed combinations, and display satisfactory mechanical properties and with no fusion zone defects such as excessive gas porosity, large cavities or cracking. Due to the relatively high level of dissolved oxygen in ETP copper, EB welds in this material are more susceptible to the formation of excessive amounts of porosity, and sound welds can only be made using a narrow range of bonding parameters. Root cavities are often observed in copper EB welds, but are considered to be inconsequential because they are embedded in the container shell and have no significant effect on the quality of the weld joint. Surface defects such as blow holes, undercutting and erratic metal overflow are promoted by high power/high welding speed combinations and appear to be the limiting factor in welding parameter selection.

Non-destructive evaluation of copper EB welds by ultrasonic inspection indicates that relatively large cavities (width and length > 0.8 mm) and dense areas of small gas pores (diameter > 0.3 or 0.4 mm) can be detected by using the pulse-echo technique/19/. Sparsely scattered gas porosity of the same size range cannot be detected, but is considered to be inconsequential with respect to the mechanical properties of copper EB welds.

In summary, test results to date show that OF copper is clearly preferred to ETP copper for the fabrication of copper nuclear fuel waste disposal containers by EB welding. Previous work/22/ suggests that there is no significant difference in electron beam weldability between OF copper and phosphorus-deoxidized copper, but this also needs to be verified by welding trials. Optimum EB welding procedures have been established for the main body of a closure weld. Future work will concentrate on the development of optimum weld initiation and termination procedures. Finally, repair welding procedures remain to be developed to deal with, for example, large cavities in the fusion zone or bond line defects due to a missed joint.

2.2.2 Gas-Metal-Arc Welding of Copper

Gas-metal-arc (GMA) welding of thick copper is considered to be difficult because the high thermal conductivity of copper necessitates the use of high preheat and/or high welding current (high heat input). Work by Japanese researchers/23/ showed that satisfactory single-vee-groove butt welds can be made in 25 mm thick ETP copper with no preheat using the GMA welding process, with high current of ~ 1000 A. Research studies performed by the Welding Institute of Canada for the container welding program also indicate that high currents (> 1200 A) are required for GMA welding of 25 mm thick copper without preheat/24/.

Preliminary welding trials at Ontario Hydro Research Division showed that preheating of 25 mm thick copper plates up to -600°C is desirable for welding at $\sim 350 \text{ A/25/}$. The cross-section of a typical copper GMA welded sample is shown in Figure 14.

At the present time the development of GMA welding procedures for welding 25 mm thick OF and ETP copper with and without preheat is in progress. The temperature excursion of the copper base metal resulting from welding and preheating cycles will be recorded and used to predict the thermal cycles at the inner wall of a copper container during GMA closure welding. The effect of preheat and welding parameters on the weld quality will also be evaluated. The test results will then be used to select the preheat/welding current combination that provides the most satisfactory weld quality along with the least amount of heating of the container inner surface. The relative GMA weldability of OF and ETP copper will also be evaluated.

2.3 Inconel 625 (In625)

Inconel 625 is one of the candidate materials for supported-shell containers. Various welding processes such as electron beam welding, resistance-heated diffusion bonding and gas-tungsten-arc welding have been evaluated for the final closure of Inconel 625 containers, although at a level of activity much less than that maintained in copper and titanium container welding studies.

2.3.1 Electron Beam Welding of In625

Early feasibility studies showed that single pass square butt electron beam welds displaying satisfactory hardness, tension and side bend test results/17/ can be made in 12.7 mm (0.5 in) Inconel 625 plates. The cross-section of a typical In625 EB weld is shown in Figure 15. A cosmetic pass was also used to make this weld. In the development of EB welding techniques for In625, it was shown that efforts should be made to reduce the extent of crown undercutting and to minimize weldment distortion. In general, however, EB welding appears to be feasible and desirable for welding thick Inconel 625. Further development of EB welding procedures for Inconel 625 is at a halt at this time, and will not be resumed unless Inconel 625 is selected as a preferred material for nuclear fuel waste disposal containers.

2.3.2 Resistance-Heated Diffusion Bonding of Inconel 625

A great deal of difficulty has been encountered in resistance-heated diffusion bonding of Inconel 625 flat strips ($\sim 6.35 \text{ mm}$ thick)/13/. During the bonding process, an oxide layer is

rapidly formed at the interface of workpieces to be joined, apparently impeding the flow of current. At lower heat inputs, no bond was formed. When the heat input was raised to a sufficiently high level to overcome the impedance of the oxide layer, the heat generation at the interface was too high and caused the formation of a poorly bonded interface with a fusion zone. Based on these test results, it is concluded that resistance-heated diffusion is not suitable for the final closure of Inconel 625 containers and no future work will be conducted in this area.

2.3.3 Gas-Tungsten-Arc Welding of In625

Gas-tungsten-arc welding studies on In625 plates are in progress to develop suitable welding procedures, and to determine weld joint configuration and fit-up tolerances for the final closure of In625 containers.

2.4 316 L Austenitic Stainless Steel

It is well recognized that austenitic stainless steels are highly susceptible to localized corrosion in aqueous chloride solutions and hence, 316 L stainless steel would be a candidate material for nuclear fuel waste disposal containers only if the vault environment were very benign/5/. Nevertheless, 316 L stainless steel is still being included in the materials evaluation program to provide a base against which to compare the corrosion performance of the other candidate materials. In this program, no specific welding projects are being carried out on 316 L stainless steel.

3.0 REMOTE CONTROLLED WELDING SYSTEMS FOR THE FINAL CLOSURE OF NUCLEAR FUEL WASTE DISPOSAL CONTAINERS

Because the used fuel is highly radioactive, the final closure welding and if necessary, repair of a loaded container must be done remotely. The automation requirements of gas-shielded arc welding processes, resistance-heated diffusion bonding and electron beam welding are identified and discussed in this section.

3.1 Gas-Shielded Arc Welding Processes

The Welding Unit of the Metallurgical Research Department at Ontario Hydro has been actively involved in the development of a computer-controlled remote arc welding capability since 1979. A summary of the work program is given in Reference 26. In collaboration with this welding automation program, the requirements of a remote arc welding system for the final closure welding of nuclear fuel waste disposal containers are being

investigated, particularly for gas-tungsten-arc welding of thin-walled titanium containers and gas-metal-arc welding of thick-walled copper containers. Areas being investigated include computer-controlled seam tracking, closed-loop feedback control of welding parameters, definition of required tolerance of welding parameters and remote-controlled repair welding requirements (ie, for inspection, grinding, gouging, cutting and welding). The steps involved in a completely automated remote-controlled arc welding operation for the final closure of nuclear fuel waste disposal containers are depicted in Figure 16.

As described in Reference 26, the Welding Unit has attained considerable expertise in electronic circuit design and computer control software for the precise motor control required in robotics systems for specialized automated welding applications. As part of the welding automation program, a commercially-available welding head for piping and cylindrical weldments has been substantially modified to allow 3-axis computer control for seam tracking and precise path control during welding. Automated seam tracking and subsequent multi-pass orbital welding have been demonstrated successfully on a 76 mm (3") pipe mock-up. However, the seam tracking optical sensor used appears to be insufficiently versatile for applications such as large diameter pipe or container welding. At the present time collection of information and evaluation of the capabilities of commercially available sensor and tracker systems is in progress. Information is also being collected concerning typical deviations in weld seam location, joint gap and misfit which may be encountered in the welding of large diameter pipes, and titanium or copper containers. Based on such information, the most suitable seam tracking/sensor system is to be selected and interfaced with our already established automated welding apparatus.

To take maximum advantage of computer-controlled automated welding, a data bank of weld joint geometry (fit-up)/welding parameters/weld deposit geometry relationships is required to enable computer selection of optimum welding parameters for every point on the weld path, as a function of local joint fit-up. Such information is being generated in the development of gas-shielded arc welding procedures for nuclear fuel waste disposal containers as described in previous sections. It has been demonstrated that the Welding Unit's PW106 microprocessor-controlled GTA welding power supply can be used to provide a multi-level capability for varying parameters along the weld path. Other commercially available microprocessor-controlled GTA and GMA welding power supplies will also be considered for

pipe and container welding studies. Both the PDP11/23 (MINC) and the 68000-based VME/10 microcomputers will be evaluated for synchronizing and controlling seam tracking and welding along the weld path.

In the area of remotely-controlled automated repair welding, a major program has recently been initiated between Ontario Hydro Research Division and the Institut de Recherche d'Hydro-Quebec (IREQ), with support from the Canadian Electrical Association, to develop a robotic system for the in-situ repair of cavitation damage in hydraulic turbine runners/26/. Many of the capabilities already developed or to be developed for this project, including surface tracking and mapping, tool path sequence control, robotic arc gouging, and welding and grinding, are relevant to container repair welding (see Figure 16) and will be monitored accordingly.

The Non-Destructive and Fracture Evaluation Section (NDFE) of the Metallurgical Research Department at Ontario Hydro has also been very active in robotics. A Unimate Puma robot has been used extensively for automated ultrasonic testing, including the development of ultrasonic inspection techniques for the container closure welds. The robot has been interfaced to a control computer to allow more detailed path sequence and real time ultrasonic signal processing. Research personnel in the Welding Unit and the NDE Section will be working closely in the development of an automated welding/inspection system for the final closure of nuclear fuel waste disposal containers.

3.2 Resistance-Heat Diffusion Bonding

A broad range of in-process quality control systems are widely used for resistance spot welding, projection welding and resistance seam welding in industry. Basically, these systems can be divided into two categories:

- i) In-process quality monitoring systems, which record one or more critical parameters during the weld or bond cycle. Information relating to weld or bond quality is obtained by automatically comparing the measured data with previously established control values.
- ii) In-process automatic quality correction systems. Such systems monitor and control one or more critical parameters during the weld or bond cycle to maintain joint quality under varying external conditions. This is achieved by automatic processing of the data to a feedback system which continuously adjusts and optimizes the welding or bonding conditions.

In recent years, resistance welding and bonding have become more reliable and precise. The present study has shown that sound titanium resistance/diffusion bonds can be made over a wide range of bonding parameters. Satisfactory surface finish and bond quality can be assured by maintaining the bonding parameters within preset limits, which can be easily established. Furthermore, commercial control systems based on monitoring of individual welding/bonding parameters, power input, and dynamic resistance are available from various manufacturers. It has also been shown that all bonding parameters can be dynamically recorded during the bonding process. This parameter record provides a permanent record of the bonding process and serves as a diagnostic tool for quality assurance and analysis.

It has also been demonstrated that lack of adequate bonding due to the presence of grease, paint and glass beads at the interface can be detected readily by ultrasonic inspection, without surface grinding/11,16/. Bond width can also be determined by this inspection technique.

Summarizing, the test results to date show that an in-process quality monitoring system combined with complete ultrasonic inspection of finished joints, would ensure the soundness of titanium resistance/diffusion bonds. In the present application, an automatic quality correction system to adjust bonding parameters according to changes in external conditions does not seem necessary.

3.3 Electron Beam Welding

Electron beam welding is being considered as a candidate process for the final closure of thick-walled copper, titanium and Inconel containers. At the present time, the main concern is to investigate the requirements of a remote EB welding system for copper containers. It has been shown that copper EB welds displaying consistently sound quality can be made by maintaining welding parameters within experimentally defined limits. Furthermore, EB welding requires close machining tolerances on fit-up. The gap between the joining edges must not exceed 0.1 mm (0.005 in). Careful container pre-fabrication and suitable fixturing is therefore essential to eliminate weld joint misfit. Also, the weld bead is narrow, such that precise alignment of the electron beam with the joint is essential to avoid missed joint defects.

In recent years, computer-controlled EB welding systems have become commercially available. These systems are very precise and welding parameters such as current and voltage can be easily kept within $\pm 1\%$ of the preset values, which is considerably less than maximum allowable variations of welding parameters for

copper EB welding. These advanced systems also generally have welding parameter monitoring and automatic seam tracking capabilities. During welding, each welding parameter affecting weld quality can be continuously monitored and dynamically displayed on a CRT. Any parameter value outside preset limits will energize a fault signal, which can also be displayed either on CRT or on a high speed printer. Such a monitoring system is very useful for quality assurance and analysis. The seam tracking capability provides the ability to automatically follow the joint to be welded and minimize the occurrence of missed joints.

In future work, fine tuning of copper EB welding procedures will be carried out to establish the limits of variation for critical welding parameters, which could then be used together with an advanced EB welding system for the final closure of copper containers.

4.0 SUMMARY OF THE CURRENT PROGRAM

It has been demonstrated that resistance-heated diffusion (R/D) bonding and pulsed current gas-tungsten-arc (GTA) welding are feasible and promising for the final closure of titanium thin-walled supported-shell containers. R/D bonding has been shown to be particularly attractive for remote joining of thin titanium (<4 mm thick). In comparison to R/D bonding, GTA welding appears to be more versatile for joining titanium over a wide range of thicknesses. However, the welding parameters must be closely controlled and adjusted according to weld joint geometry and fit-up to ensure satisfactory weld quality. Electron beam (EB) welding has been shown to be a viable candidate process for the final closure of thick-walled titanium stressed-shell containers.

EB welding is an ideal process for joining thick copper without preheating. Optimum EB welding procedures have been established for the main body of a closure weld. Future work will concentrate on the development of optimum weld initiation and termination procedures. Preliminary gas-metal-arc (GMA) welding studies have shown that extremely high welding current (>1000 A) is required to join thick copper (>25 mm) without preheating. Development of GMA welding procedures for welding 25 mm thick copper is in progress and the test results will be used to select the preheat/welding current combination that provides the most satisfactory weld quality along with the least amount of heating of the contents of the container.

R/D bonding has been shown to be unsuitable for joining 6.35 mm thick Inconel 625 plates due to the rapid formation of an interfacial oxide. Test results have also shown EB welding to be a

feasible process for joining thick Inconel 625 plates (>12.7 mm). At the present time, the establishment of suitable GTA welding procedures for joining Inconel 625 is in progress.

A remote-controlled arc welding capability is being developed including seam tracking and welding parameter optimization by computer selection, particularly for gas-tungsten-arc welding of titanium and gas-metal-arc welding of copper.

ACKNOWLEDGEMENTS

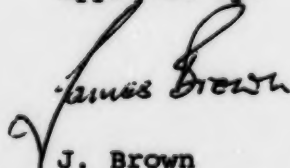
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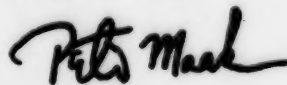
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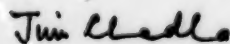
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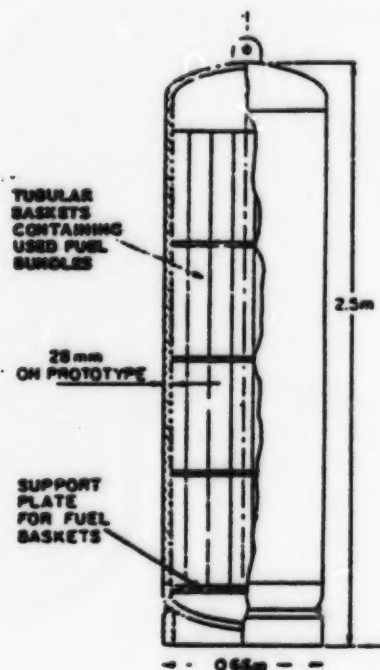


FIGURE 1
DESIGN DETAILS OF 316 L STAINLESS STEEL
STRESSED-SHELL PROTOTYPE CONTAINER

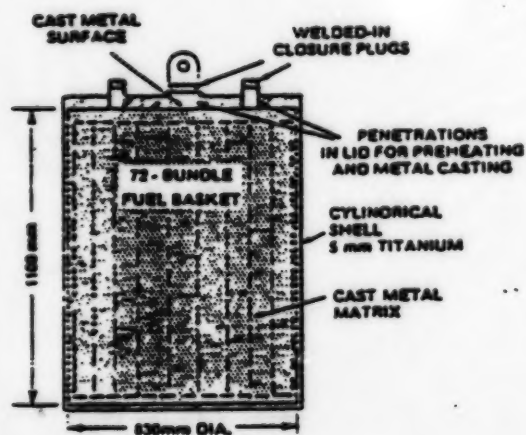


FIGURE 2
CONCEPTUAL DESIGN OF A METAL-MATRIX
SUPPORTED-SHELL CONTAINER

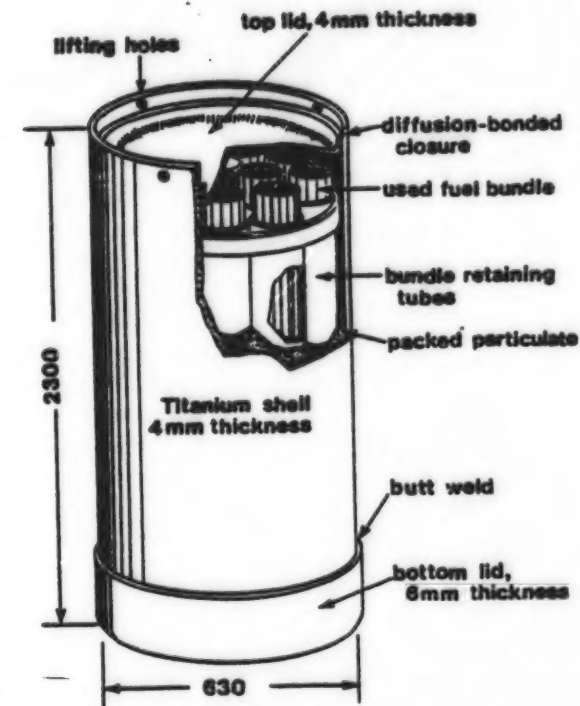


FIGURE 3

DESIGN DETAILS OF A PACKED-PARTICULATE SUPPORTED-SHELL
FUEL ISOLATION CONTAINER

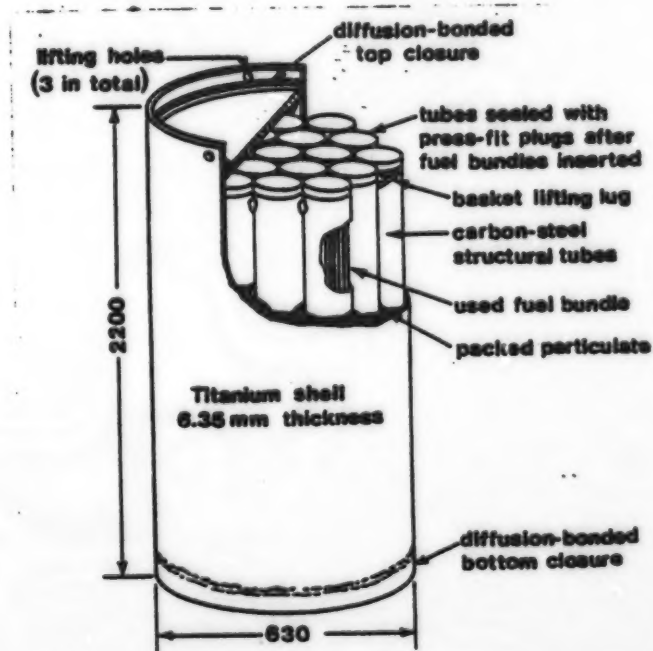


FIGURE 4

DESIGN DETAILS OF THE PROTOTYPE STRUCTURALLY-SUPPORTED
FUEL ISOLATION CONTAINER

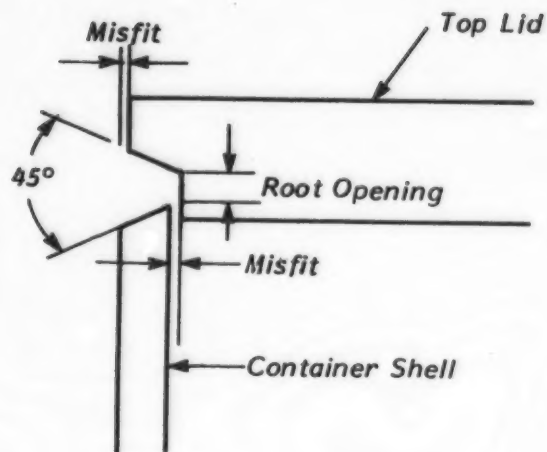


FIGURE 5
RECOMMENDED WELD JOIN DESIGN FOR THE FINAL CLOSURE OF
SUPPORTED-SHELL TITANIUM CONTAINER
USING THE GAS-TUNGSTON ARC-WELDING PROCESS

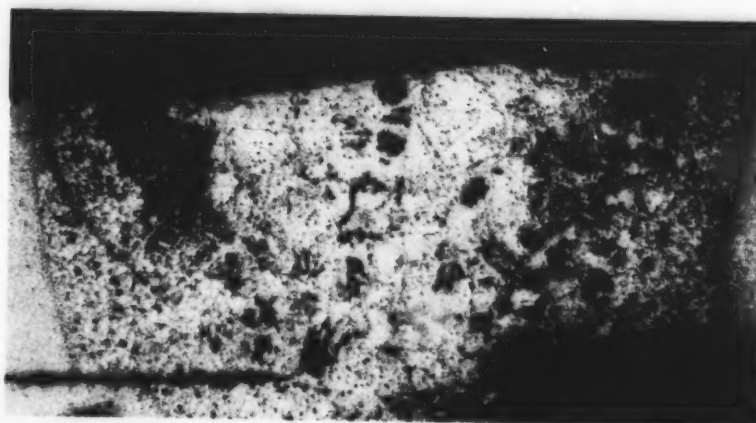


FIGURE 6
CROSS-SECTION OF A TYPICAL TITANIUM
GAS-TUNGSTON ARC-WELD

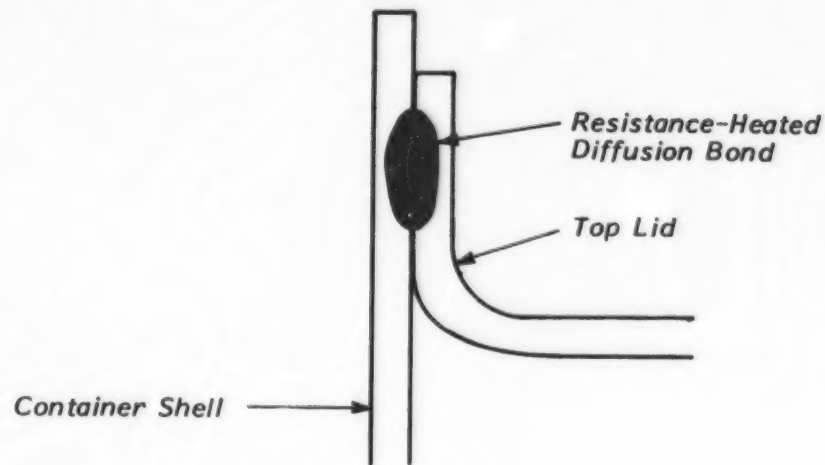


FIGURE 7
RECOMMENDED WELD JOINT DESIGN FOR
THE FINAL CLOSURE OF SUPPORTED SHELL TITANIUM CONTAINERS
BY RESISTANCE-HEATED DIFFUSION BONDING



FIGURE 8
CROSS-SECTION OF A TYPICAL TITANIUM RESISTANCE-HEATED
DIFFUSION BOND, MAG 5X

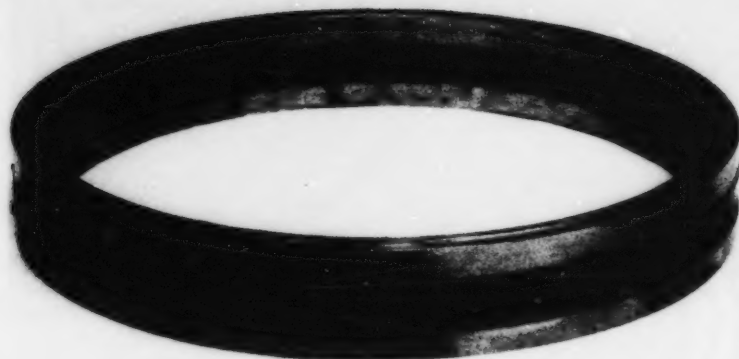


FIGURE 9
A TYPICAL TITANIUM RESISTANCE-HEATED DIFFUSION
BONDED RING MOCK-UP, MAG 2.9X

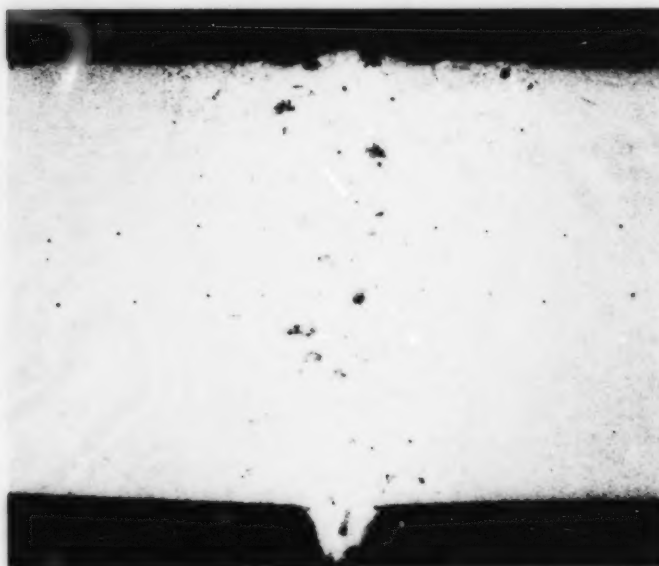


FIGURE 10
CROSS-SECTION OF A TYPICAL TITANIUM
ELECTRON BEAM WELD, MAG 5X

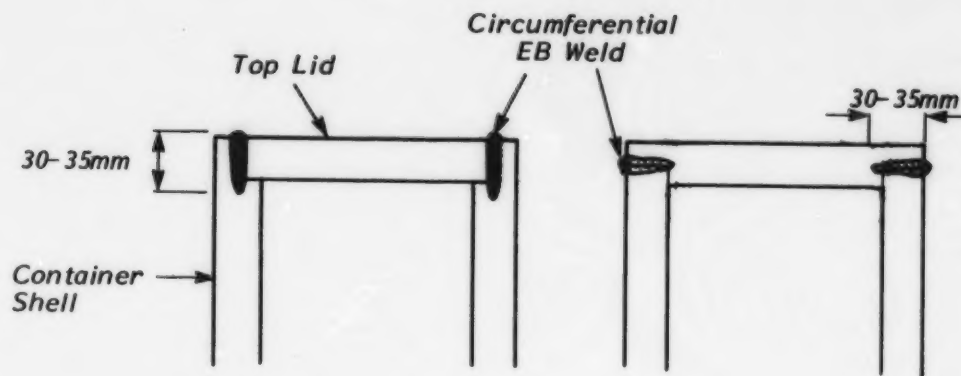


FIGURE 11
RECOMMENDED WELD JOINT DESIGN FOR THE FINAL
CLOSURE WELDING OF THICK-WALLED SUPPORTED-SHELL
COPPER CONTAINERS USING THE ELECTRON BEAM WELDING PROCESS



FIGURE 12
A TYPICAL COPPER ELECTRON BEAM WELDED
PIPE MOCK-UP, MAG 4.3X

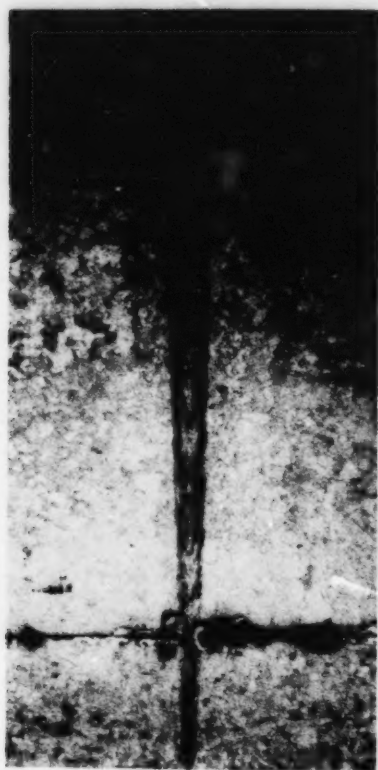


FIGURE 13
CROSS-SECTION OF A TYPICAL OXYGEN-FREE
COPPER ELECTRON BEAM WELD, MAG 3.5X

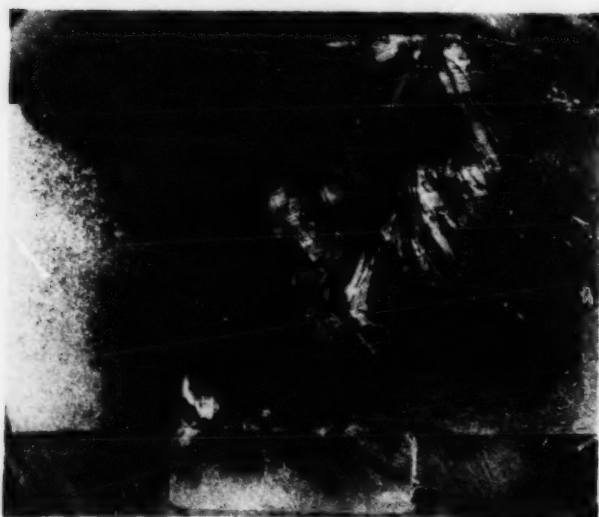


FIGURE 14
CROSS-SECTION OF A TYPICAL
COPPER GAS-METAL-ARC WELD, MAG 2X

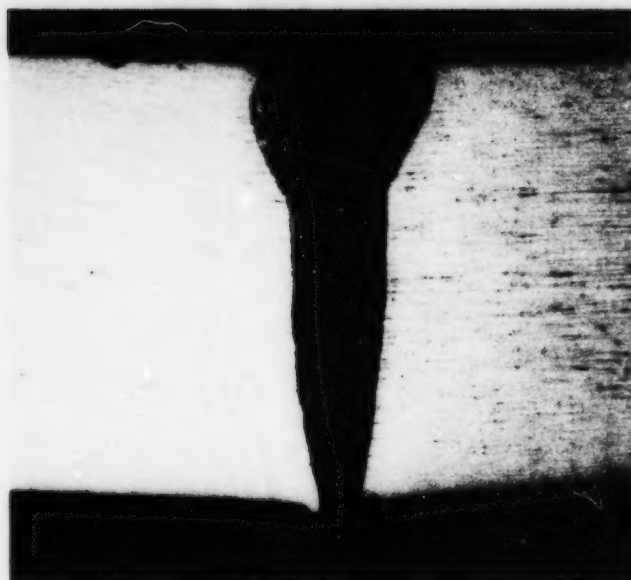


FIGURE 15
CROSS-SECTION OF A TYPICAL INCONEL 625 ELECTRON
BEAM WELD, MAG 5X

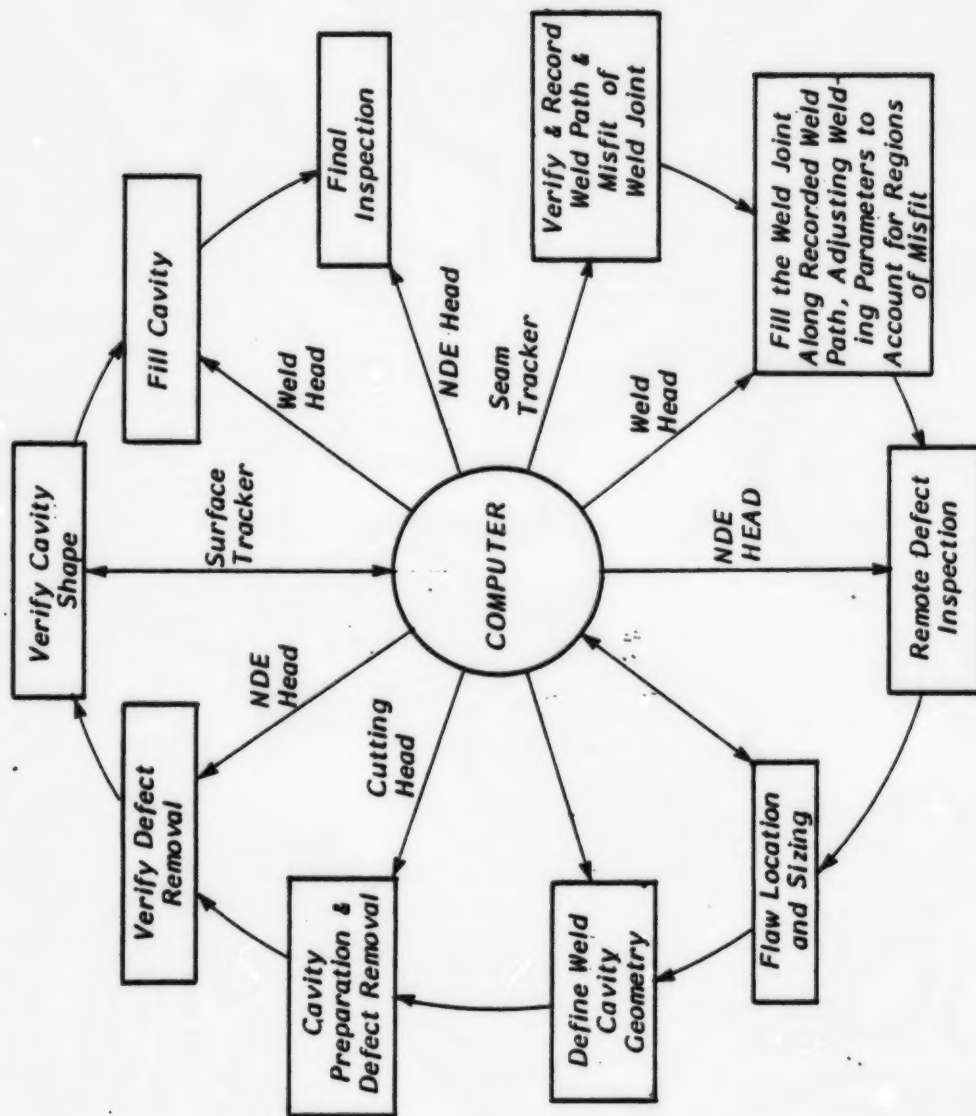


FIGURE 16
 AUTOMATED SYSTEM FOR REMOTE FINAL CLOSURE WELDING INSPECTION
 AND REPAIR WELDING OF NUCLEAR FUEL WASTE DISPOSAL CONTAINERS